Exploring Techniques for Improving Retrievals of Bio-optical Properties of Coastal Waters

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LONG-TERM GOALS

Development of algorithms for improved retrievals of inherent water optical properties (IOP) from satellite imagery of coastal waters with current and future sensors utilizing: 1) NIR and UV channels, 2) water polarization characteristics and 3) advanced atmospheric correction schemes.

OBJECTIVES

Analysis of methodologies for the enhancement of algorithms for IOP retrieval from reflectance spectra based on additional measurements in NIR and UV through: a) the use of reflectance characteristics obtained from NIR measurements as additional constraints in basic inversion models, b) expansion of modeled and measured reflectance spectra and bio-optical models of coastal waters into the UV zone for the improved separation of CDOM and phytoplankton components.

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Utilization of underwater and above water polarization components of reflectance spectra for the improvement of particle type discrimination and algorithm development through: a) the simulation of polarization components of reflectance for coastal water environments using polarized radiative transfer and b) measurements of polarization characteristics in field conditions to validate radiative transfer modeling and assess possibilities for the separation of organic and inorganic particulate components.

Improvement in retrievals of water leaving radiances for productive coastal waters obtained by adding the 412nm channel to the SWIR coastal algorithm Improve on existing atmospheric correction algorithms in highly productive coastal waters by combining both long wave atmospheric channels with shortwave water leaving constraints at 412nm along with a more representative aerosol database.

APPROACH

Analysis of methodologies for the enhancement of algorithms for IOP retrieval from reflectance spectra based on additional measurements in NIR and UV

The NIR peak in reflectance spectra from coastal waters contains important information about chlorophyll concentration Chl and other parameters which can be used in retrieval algorithms. Elastic component of the spectra overlaps with the chlorophyll fluorescence in this spectral zone and the separation of these two components is useful in retrievals; in addition the magnitude of the fluorescence component itself is related to Chl and other water parameters. Efforts are made to determine typical fluorescence quantum yields in coastal waters which can be then used in modeling and retrievals.

UV channels in addition to VIS and NIR channels can further assist in separation of CDOM and Chl absorption components. To analyze these impacts, a previously available Hydrolight simulated database of reflectances for a wide variety of coastal water conditions was expanded to cover the 300-400 nm range, and several algorithms were used to test improvements inj retrievals resulting from the inclusion of the UV channels.

Utilization of underwater and above water polarization components of reflectance spectra for the improvement of particle type discrimination and algorithm development

The purpose of this part of the work is to obtain underwater and above water angularly resolved hyperspectral measurements of the degree of polarization (DOP) in coastal environments that present a wide variability of water constituents with a newly developed Stokes vector spectroradiometer, and compare them with simulated data. Differences in polarization signatures of inorganic and organic particles can be further used in the improved interpretation of remote sensing signals and in comparisons with the polarization signatures of important naval targets as supplied by NRL with the goal of improvement of visibility and detection.

Improvement in retrievals of water leaving radiances for productive coastal waters obtained by adding the 412nm channel to the SWIR coastal algorithm

To avoid problems with operational NIR algorithm [5-7], an algorithm using short wave infrared (SWIR) bands (i.e. MODIS 1240 and 2130nm) was proposed for operational retrieval of coastal water color and tested within SeaDAS [8]. However, at these long wavelengths, the atmospheric reflectance itself is significantly weaker and spectral features due to absorbing aerosols or fine urban modes are particularly difficult to resolve. Therefore, the retrieval error for water leaving radiances in the VIS channels using the SWIR bands is larger than that obtained using the NIR bands. For these reasons, we have adopted an approach where an additional constraint on aerosol path reflectance at 412nm channel is applied to the SWIR retrieval algorithm. The approach we take is as follows: a) good statistical estimates of the 412 water leaving radiance is obtained directly from in-situ measurement statistics or bio-optical estimators b) Regional aerosol models using AERONET measurements to account for regional variability are used for developing more representative LUT's c) An assessment of aerosol retrieval and associated water leaving reflectance retrievals was made.

WORK COMPLETED

- Variability of the fluorescence quantum yields were determined for a variety of coastal water conditions based on the simultaneous measurements of reflectances and IOPs in the Chesapeake Bay, LIS and NYC vicinity, showing that mean values are close to our previously published [1] indirect estimations based on the shift of the NIR reflectance peak from the fluorescence peak at 685 nm.

- The performance of the over constrained linear inversion algorithm with and without the addition of UV channels for retrieving the IOP components from remote sensing reflectance was tested on synthetic data, and showed some improvements with the inclusion of UV bands.

- A new Stokes vector spectroradiometer was developed and used to obtain accurate and reliable *in situ* hyperspectral and multi-angular measurements of polarization characteristics of the underwater and above water light field. The angular and spectral dependence of the DOP was analyzed and correlated to the water constituents.

- Experimental measurements were compared with simulated ones using a Monte Carlo radiative transfer code for the atmosphere-ocean system. These showed excellent agreement.

- A statistical analysis of the mean 412 reflectance and the bio-optical estimator approach was established. This provides a quantitative water leaving reflectance constraint.

- A regional aerosol LUT was developed which emulates the variability observed in AERONET retrievals.

- Direct intercomparisons were made of SeaDAS, insitu and regional algorithms which show potential for improvement.

RESULTS

Analysis of methodologies for the enhancement of algorithms for IOP retrieval from reflectance spectra based on additional measurements in the NIR and UV

Retrieval of the fluorescence quantum yield, η, takes advantage of hyperspectral field measurements of water absorption and attenuation which are combined with remote sensing reflectance and used to determine the magnitude of the sun induced chlorophyll fluorescence (SICF) in highly productive coastal waters.

Vertical distributions of high resolution absorption and attenuation spectra are fed into the radiative transfer Hydrolight program to properly characterize the elastic reflectance spectra. LSQ fitting is then applied to the in-situ remote sensing reflectance to decompose the signal into elastic scattering spectra and chlorophyll fluorescence spectra to obtain the SICF radiance.

With chlorophyll fluorescence and phytoplankton absorption retrieved, η is derived using a depth integrated fluorescence model. Distributions of the fluorescence quantum yield for two regions are shown in Fig. 1 with mean values of 0.33%±0.17% which are close to our previous indirect estimates based on the analysis of the position of the NIR reflectance peak [1].

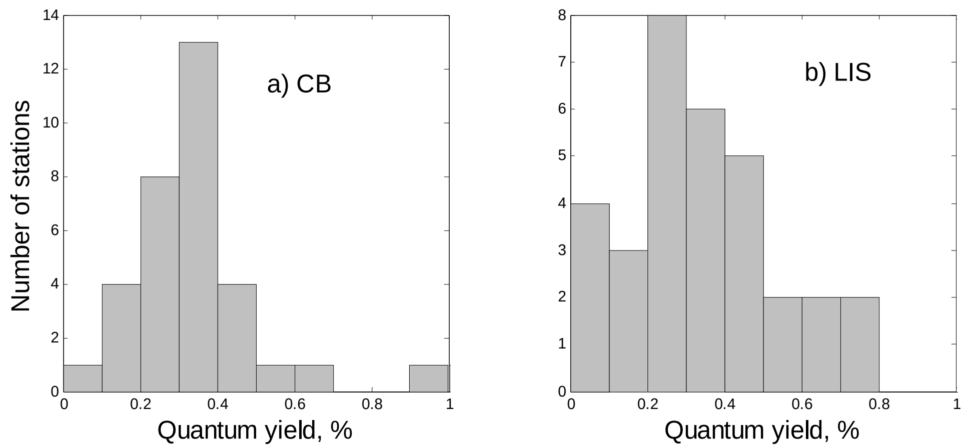


Fig. 1. Distribution of the fluorescence quantum yield: a) Chesapeake Bay, b) LIS and NYC vicinity.

To test the value of UV channels for the retrieval of IOP from reflectance spectra, the data base of reflectance for coastal waters [1] was expanded into the UV zone using a Hydrolight UV extension. The over constrained linear inversion algorithm [2] was then applied for the retrieval of absorption coefficients $a_{pg}(440)$ (total), $a_{ph}(440)$ (phytoplankton), $a_{dg}(440)$ (CDOM) and backscatter coefficients $b_{bp}(440)$, where R_{rs} values at 412, 443, 490, 510, 555, and 667 nm denote the baseline augmented by UV at 350, 380 nm. Comparisons were made separately for low minerals $C_s < 1$ mg/l and high minerals $1<C_s<100$ mg/l. It is shown that for low minerals, the correlation coefficients r^2 increased from 0.85-0.88 to 0.89-0.93 with inclusion of UV channels. For high mineral cases, changes were not noticeable.

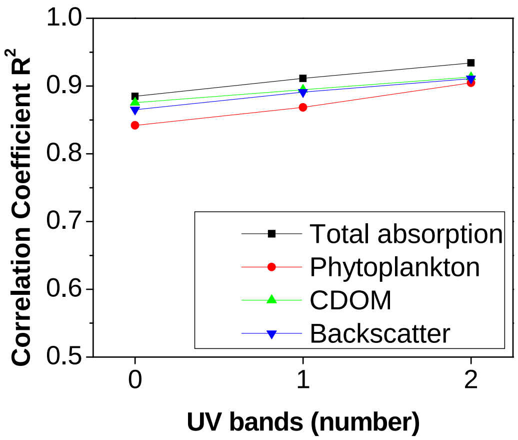


Fig. 2 Improvement in IOP retrieval with the inclusion of UV bands

Utilization of underwater and above water polarization components of reflectance spectra for the improvement of particle type discrimination and algorithm development

Our newly developed Stokes vector spectroradiometer consists of three Satlantic Hyperspectral radiance sensors mounted on a scanning system controlled by an underwater electric stepper motor as shown in Fig. 3. The motor rotates the sensors in a vertical plane in a specific angular range, which was adjusted in accordance with the solar altitude angle, in order to cover the full 0-180º range of scattering angles. Linear polarizers are attached in front of the sensors; 0º (vertical), 90º (horizontal) and 45º.

Measurements were taken during a recent cruise on R/V "Connecticut" in coastal areas of New York Harbor - Sandy Hook, NJ region, on July 21-23 2008 with ([Chl] ≈ 2-8 mg/m^3, minerals Cs ≈ 1-2 mg/l). Fig. 4 gives two typical plots (Station 1, Fig. 4a, and Station 8, Fig. 4b) showing the Degree of Polarization (DOP) vs. scattering angle, recorded in the main scattering plane, at 1m depth, and with a maximum DOP of approximately 0.4 at 410nm at Station 1. Note the reduction of DOP at Station 8 (Fig. 4b) due to the diffuse illumination because of clouds.

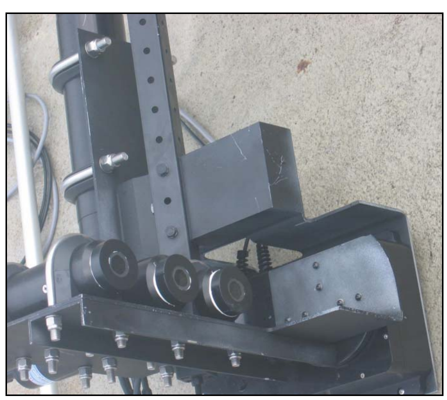


Fig. 3. The underwater instrument developed by the Optical Remote Sensing group at City College of New York.

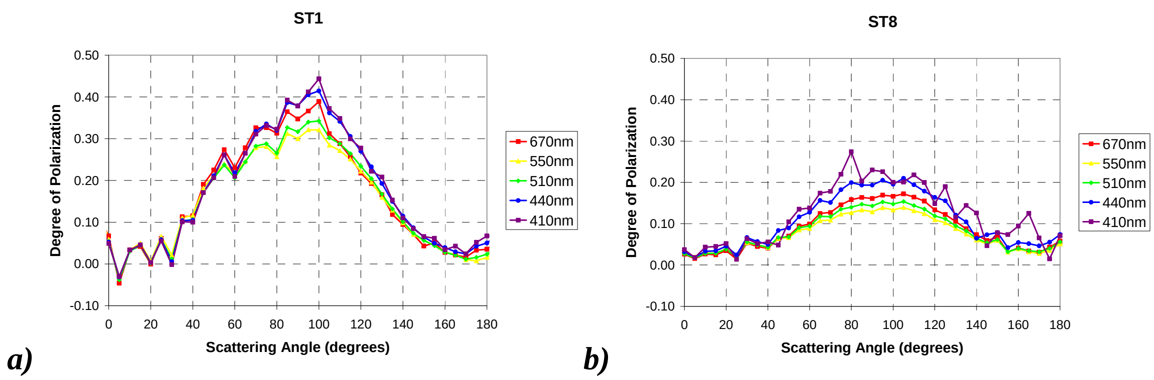


Fig. 4. Plots of the DOP vs. scattering angle.
The instrument is located in the principal plane 1m below water.

In Fig. 5a, we observed changes in the DOP which are consistent with changes in the absorption spectrum measured with an AC-9 instrument (WET Labs) shown in Fig. 5b. As the absorption coefficient increases, multiple scattering events are reduced and DOP increases. The second minimum, however, between 600 and 700nm cannot be related to the absorption curve of Fig. 5b. At the present time we believe this to be related to chlorophyll fluorescence in this spectral interval.

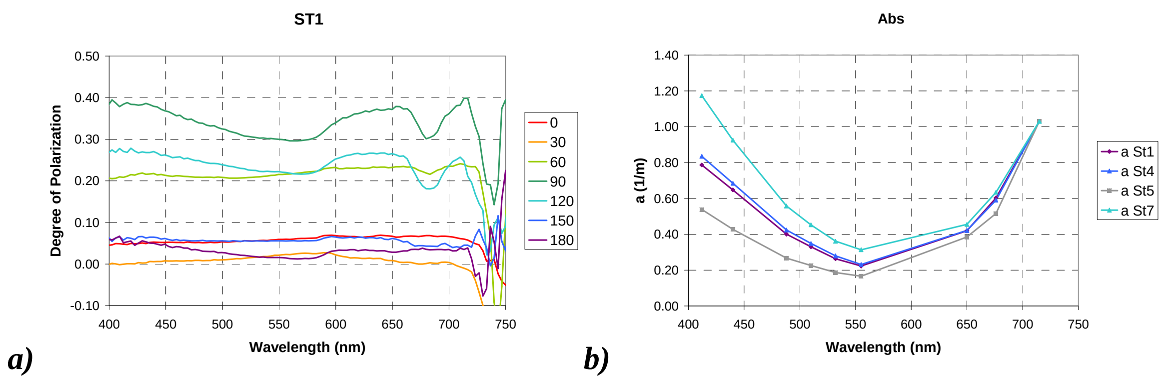
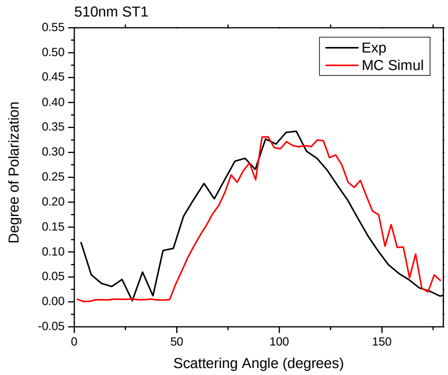
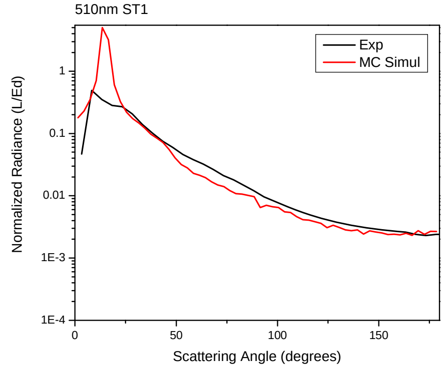


Fig. 5 a) Spectral dependence of the DOP, b) total absorption spectra

Total radiances and DOPs experimentally measured were compared with simulations using Monte Carlo radiative transfer codes [3,4]. As seen in figure 6, the agreement between the magnitudes of the measured and modeled DOP is quite good considering the proximity of the radiometer to the surface.



a)



b)

Fig. 6. Comparison of modeled and measured data for 510 nm, Station 1, a) DOP, b) normalized radiance.

Above water measurements of DOP were consistent with the below water surface measurements. Agreement between measured and simulated parameters will be further verified for a wider variety of coastal water conditions including waters with high Chl and mineral loadings.

Improvement in retrievals of water leaving radiances for productive coastal waters obtained by adding the 412nm channel to the SWIR coastal algorithm

Statistical estimates of the 412 water leaving radiance**:** Two methods for estimating the $[\rho_{wn}(412)]$ parameter were considered. In the first approach, we can determine a best estimate by simply using the mean value obtained from large scale in-situ measurements, which was contrasted with a bio-optical estimator approach, previously introduced [3.5] to correct for absorbing aerosols. In particular, we find that the mean estimator significantly outperforms the "biased" bio-optical estimator for the Chesapeake region. Ultimately, $\rho_{wn} = \bar{\rho}_{wn} + \Delta\rho_{wn}$ where $\Delta\rho_{wn}^{1\sigma} = .003$ at (1σ) and $\Delta\rho_{wn}^{2\sigma} = .005$.

The AERONET atmospheric aerosol models were generated with the SHARM radiative transfer code using 159 phase functions (aerosol models) and 10 different AOD levels (i.e. 1590 atmospheres). From this set, we can then use multichannel TOA measurements (as well as a-priori estimates of water leaving reflectance at 412nm) to constrain the aerosol model and optical depth simultaneously and obtain the statistics of aerosol retrieval including mean and standard deviation etc. We also find that a large number of high angstrom coefficient aerosol models $1 \le \log[\varepsilon_{aeronet}(412,2130)] \le 3.5$ are observed in AERONET as opposed to SeaDAS LUT's $0 \le \log[\varepsilon_{SeaDAS}(412,2130)] \le 2.5$. In addition, the effect of absorbing aerosols whose affects are increased in the blue (due to enhanced Rayleigh-aerosol interaction) are not completely represented by SeaDAS.

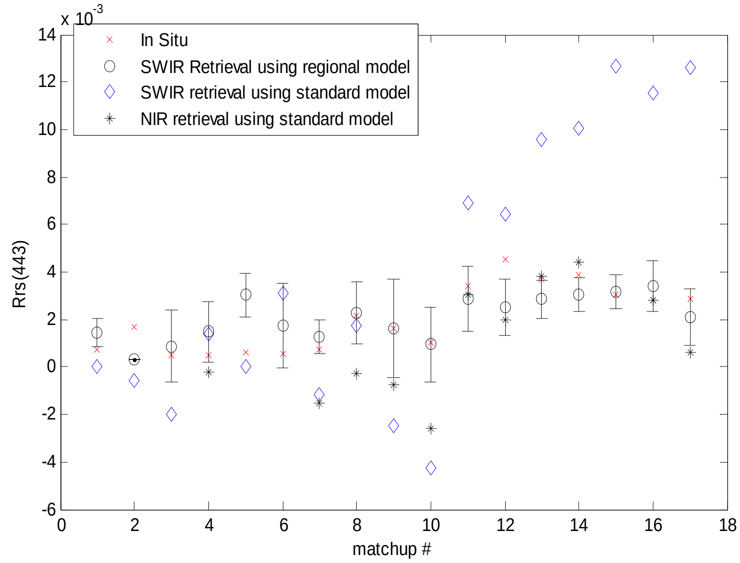


Fig. 7. Comparison of in situ measurements of normalized water leaving reflectance of SWIR retrieval using standard processing and regional model.

Once the LUT's are calculated, retrieval is based on finding atmospheres in the LUT which simultaneously satisfy all the Dark Pixel (Radiometric) channel constraints as well as the water leaving constraint [9]. Based on these atmospheres, we can get an estimate of the water leaving signal for each case. The retrieval is simply the mean of all these water leaving signals. This approach was tested on data obtained in the Chesapeake. We first compare, in Fig. 7, the remote sensing reflectance obtained from our algorithm with the standard SWIR model as well as the NIR algorithm (when possible). Although neither retrieval approach seems completely satisfactory, we do note the removal of negative retrievals in our approach, which otherwise occur in the standard processing due to the presence of a moderately absorbing aerosol modes discussed above. This undesirable feature is also seen when the NIR algorithm is used. We also see significant improvement using our constrained regional algorithm retrieval applied to insitu data for matchup sites 11-17 in comparison to the SWIR algorithm. These matchups occur in the coastal ocean outside the Chesapeake Bay area where the NIR algorithm is expected to be superior to the SWIR, which is indeed the case. We have also explored the algorithm performance based on comparison of water leaving radiances. The results are given in Fig. 8. We first note (panel b) the dramatic anomalous negative Rrs at 443 nm from SeaDAS, together with the fact that that the effect is strongly stratified between the west (negative) and east (positive) shorelines. This is removed in the regional processing. The results at 551nm are less dramatic since the effects of aerosol are less pronounced and the overall water leaving signal in most cases is significantly larger than at 443nm. We also observe that our constrained regional retrieval does not find a suitable solution in all cases where SeaDAS retrieval was successful. In particular, the narrow western tributaries as well as a gap near the center of the Bay were unsuitable for retrieval. These regions are clearly contaminated and in anomalous bright reflectance patches due to either inadequate cloud mask, or in the case of the tributaries, to possible ground reflectance contamination from the surrounding shore. These questionable regions are being routinely processed by SeaDAS, resulting in dramatic anomalies in the retrieved Rrs values as well as the aerosol optical depth.

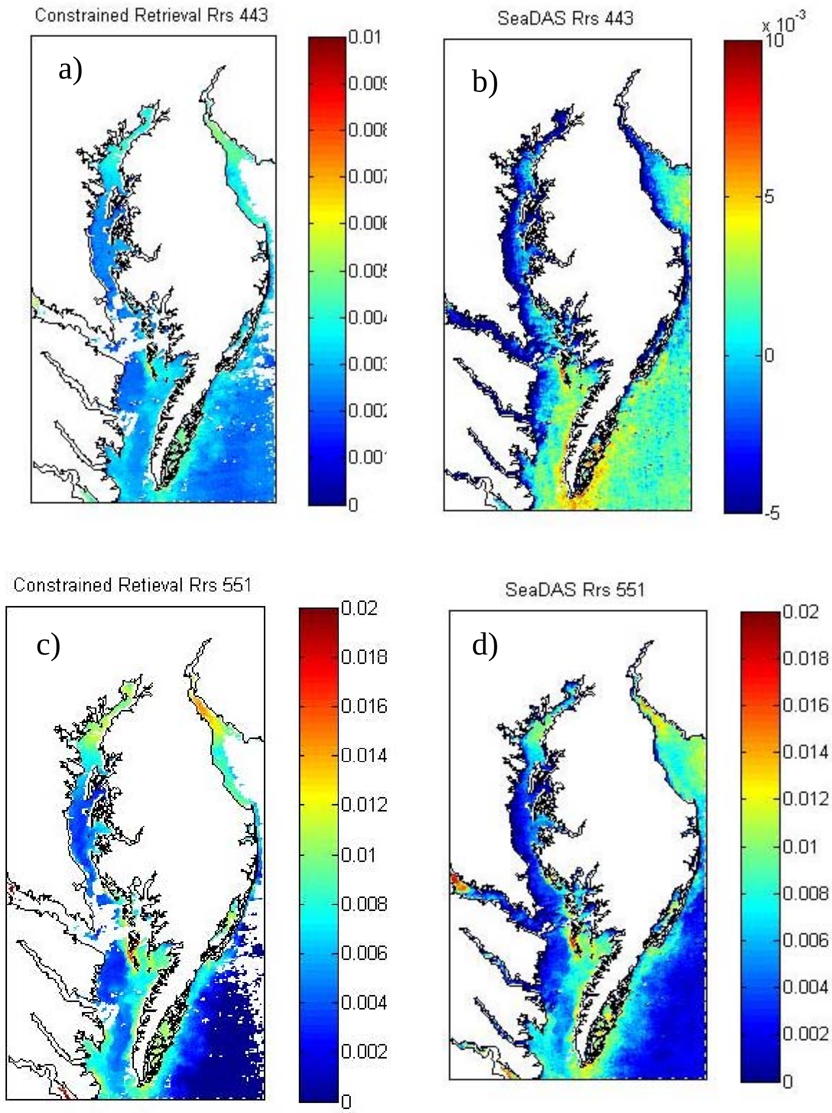


Fig. 8. Rrs reflectance comparisons a) constrained retrieval at 443nm b) SeaDAS retrieval at 443nm c) constrained retrieval at 551nm d) SeaDAS retrieval at 551nm

IMPACT/APPLICATIONS

Current algorithms for the retrieval of water optical properties based primarily on the spectral features in the blue-green region, produce significant errors in coastal waters. New approaches, which include additional spectral bands in UV and NIR as well as water polarization characteristics, should lead to retrieval improvements in complex coastal environments. In addition, accurate measurements of water polarization properties on angular and spectral scales, coupled with the radiative transfer simulations, should be helpful in the improvement of in-water visibility and detection of naval targets.

Atmospheric correction plays a crucial role in all coastal ocean algorithms. This effort will hopefully lead to an operational module which can be used in certain domains where the 412 reflectance is expected to be sufficiently small. This clearly requires many more simulations to determine which regions are suitable for this approach. In addition, a much sparser LUT needs to be developed since the current approach uses too many aerosol models.

RELATED PROJECTS

This ONR project, on improvement of retrieval of bio-optical properties, benefits from the leveraging of funding by NOAA CREST in which remote sensing of coastal waters is an important component.

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